TITLE
ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR**
EDITORS

Theory of Formation of Massive Stars via Accretion

Harold W. Yorke

Jet Propulsion Laboratory, California Institute of Technology, MS 169-506, 4800 Oak Grove Drive, Pasadena, CA 91109

Abstract. Radiative effects strongly hinder the formation of massive stars via accretion. A necessary condition for accretion growth of a hydrostatic object up to high masses $M \gtrsim 20\,\mathrm{M}_\odot$ (rather than coalescence of optically thick objects) is the formation of and accretion through a circumstellar disk. These disks will be photoevaporated on a timescale of $\sim 10^5$ yr, similar to the accretion timescale, and be observed as UCHIIs.

Collapse simulations with grey radiation transfer display significantly different results from corresponding frequency-dependent simulations. A single example of a 60 $\mathrm{M}_\odot$ molecular core with resulting stellar masses of $M_{\rm final}^{grey} = 20.7\ \mathrm{M}_\odot$ and $M_{\rm final}^{\nu-dep} = 33.6\ \mathrm{M}_\odot$ is briefly discussed.

In order to include the effects of accretion in modifying the central source's luminosity evolution, a semi-analytical scheme for augmenting existing evolutionary tracks of pre-main sequence protostars is introduced and discussed. It is shown that the "birthline", i.e. the equilibrium position of fully convective, deuterium-burning stars in the HR diagram with cosmic deuterium abundance, is — strictly speaking — unattainable via accretion for stars more massive than 1 $\mathrm{M}_\odot$.

1. Introduction

Our understanding of the formation of massive stars is still rather limited. Because of their high luminosities we can expect radiative acceleration to significantly influence this process; we cannot simply "scale up" theories of low mass star formation (see Table 1 for a comparison). Furthermore, OB stars form in clusters and associations; their mutual interactions via gravitational torques, powerful winds and ionizing radiation contribute further to the complexity of the problem.

2. What is the Problem?

Massive stars ($M \gtrsim 10\ \mathrm{M}_\odot$) are difficult to form, more difficult than is generally appreciated. Obviously, we must have

$$M_* = \int_0^t \left[\dot{M}_{\rm acc}(t') - \dot{M}_{\rm out}(t')\right]\, dt' \gtrsim 10\ \mathrm{M}_\odot \quad , \tag{1}$$

Table 1. Comparison of low mass and high mass star formation

massive ($M \gtrsim 10$ M$_\odot$)	low mass ($M \lesssim 3$ M$_\odot$)
H-burning starts before accretion has stopped and before optically visible	slow Kelvin-Helmholtz contraction to main sequence, even after optically visible
radiative acceleration in envelope will become more important than gravity	gravity dominates radiative acceleration
no optically visible massive star has optically thick disk → rapid disk dissipation *or* no disks formed?	30%–50% of optically visible young ($\lesssim 10^7$ yr) PMS stars have massive disks
associated with powerful IR sources ($\gtrsim 10^3$ L$_\odot$), UCHIIs H_2 shock emission, massive outflows, jets, H_2O masers	association with weak IR sources ($\lesssim 10^2$ L$_\odot$), CTTS, WTTS, molecular outflows, jets, ...
form under "special" conditions in preferred locations?	form continuously in dense molecular clouds?
upper mass limit?	IMF at low mass limit?

i.e., the infall (accretion) rate $\dot{M}_{\rm acc}$ must greatly exceed the outflow rate $\dot{M}_{\rm out}$ during a significant proportion of the formation process. A necessary condition for accretion to occur is the acceleration due to gravity must exceed the outward directed radiative acceleration of the embryo source. Whereas gravity GM_*/r^2 increases linearly with mass, the radiative acceleration of dusty material $\kappa L/4\pi r^2 c$ is proportional to the stellar luminosity which increases as a high power of stellar mass. Thus, to allow infall we require

$$\frac{\kappa_{\rm eff} L}{4\pi r^2 c} < \frac{GM_*}{r^2} \quad \text{with} \quad L = L_* + L_{\rm acc} \quad , \tag{2}$$

which translates into

$$\kappa_{\rm eff} < 130 \ {\rm cm^2\, g^{-1}} \left[\frac{M_*}{10 \ {\rm M_\odot}}\right] \left[\frac{L}{1000 \ {\rm L_\odot}}\right]^{-1} \tag{3}$$

This condition defines the maximum effective opacity $\kappa_{\rm eff}$ of accretable material. The (proto-)star's luminosity is given by the sum of its intrinsic luminosity and the luminosity emitted in the accretion shock fronts.

Dusty material generally has a very high opacity (Fig. 1); for the "hardness" of radiation expected from main sequence stars of 5 M$_\odot$ and higher, the net force

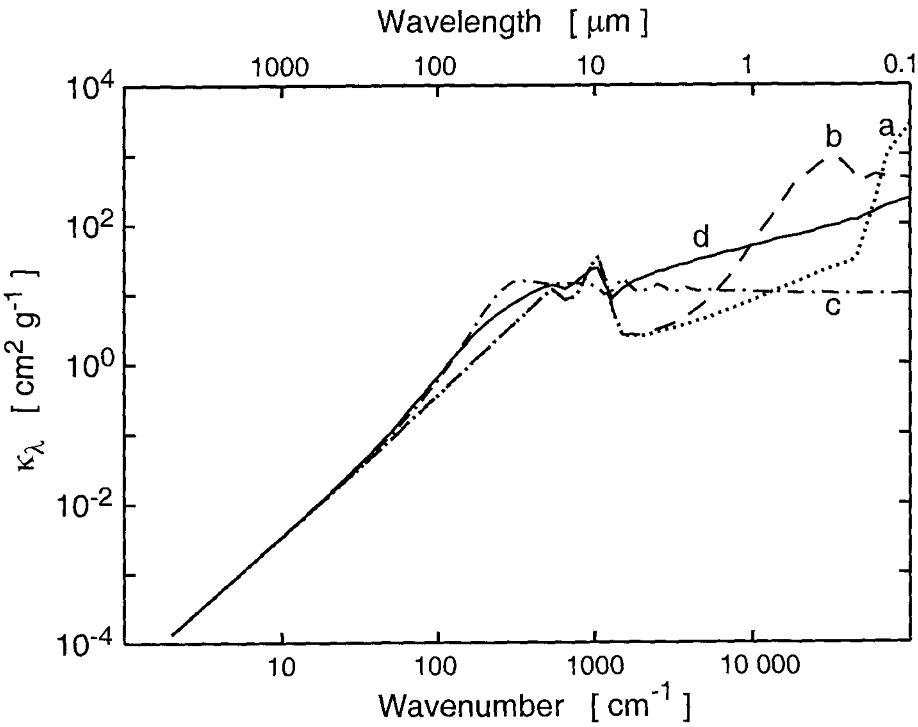

Figure 1. Specific extinction coefficients of dusty gas with a dust to gas mass ratio of 0.01 under the assumption that a) all grains have $a = 5$ nm; b) all grains have $a = 0.1$ μm; c) all grains have $a = 5$ μm; d) MRN distribution (Mathis et al. 1977).

on typical dusty interstellar material ($\kappa \gtrsim 200$ cm^{2}g^{-1}) is directed away from the star (c.f. Fig. 2).

3. How does Nature solve this Problem?

To allow further growth of an already existing stellar embryo at least one of the following conditions must be met: a) $\kappa_{\rm eff}$ must be significantly lower than its ISM value for optical/UV radiation; b) The effective luminosity must be reduced; or c) "gravity" must be increased.

a) Reduce $\kappa_{\rm eff}$:
As evident in Fig. 1 $\kappa_{\rm eff}$ can be significantly lower than its ISM value if the radiation field "seen" by the accreting material is shifted from the optical/UV into the far infrared or if most of the dust is destroyed. In their pioneering efforts Kahn (1975) and Wolfire & Cassinelli (1987) studied the 1D spherically symmetric accretion problem for massive star formation with emphasis on the dust opacity. Indeed, the latter authors concluded that massive stars can only form if the dust has been significantly modified, assuming an accretion flow that is steady-state and spherically symmetric. Of course, accretion may be non-steady and/or non-spherically symmetric and this basic premise may be invalid.

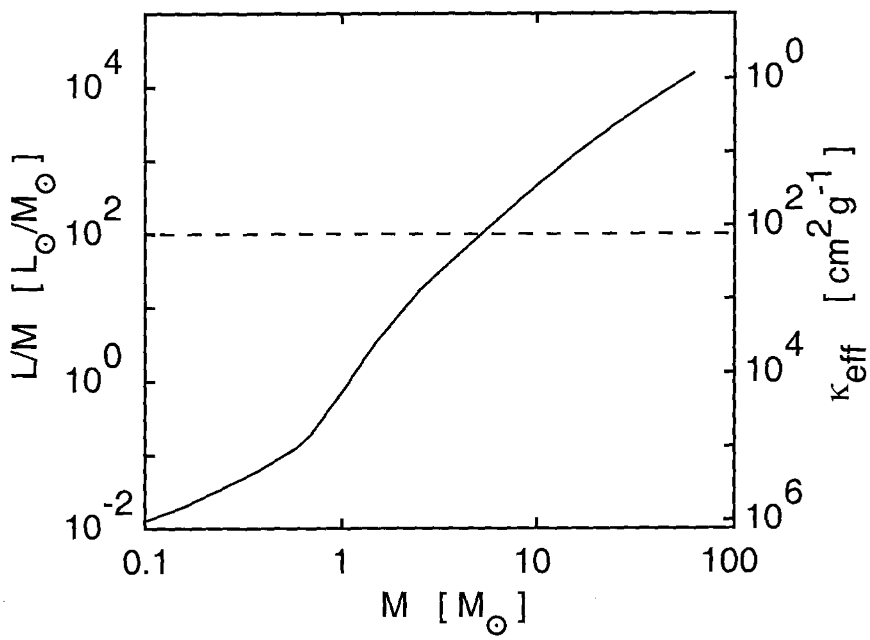

Figure 2. Luminosity to mass ratio (*solid line, left axis*) for main sequence stars. Using equation 2 this translates into a critical effective opacity for main sequence stars that allow accretion of material (*right axis*). With the dotted line I show how a "typical" value for ISM opacity translates into an upper mass limit of 5 $M_\odot$.

Another possibility to reduce the effective opacity is the accretion of optically thick "blobs". In this case

$$\kappa_{\rm eff} = \pi R^2_{\rm blob}/M_{\rm blob} \tag{4}$$

As a particular subset of this family of solutions Bonnell et al. (1998) considered building up massive stars by coalescence of lower mass stars within a stellar cluster (see also the contribution by Bonnell et al. 2001, this volume).

Modifications to the opacity due to coagulation of dust and dust destruction processes during the collapse phase were calculated by Suttner & Yorke (2001) for three different detailed dust models (compact spherical particles, fractal BPCA grains, and fractal BCCA grains). Results are shown in Fig. 3. Using a 2D (axial symmetry assumed) code that also followed the dust dynamics of 30 individual dust components, they find that even during the early collapse and the first $\sim 10^4$ yr of dynamical disk evolution, the initial dust size distribution is strongly modified. Close to the disk's midplane coagulation produces dust particles of sizes of several $10\,\mu$m (for compact spherical grains) up to several mm (for fluffy BCCA grains), whereas in the vicinity of the accretion shock front (located several density scale heights above the disk), large velocity differences inhibit coagulation. Dust particles larger than about $1\,\mu$m segregate from the smaller grains behind the accretion shock. Due to the combined effects of coagulation and grain segregation the infrared dust emission is modified. Throughout the accretion disk a MRN dust distribution provides a poor description of the general dust properties. Nevertheless, the net effect on *radiative* forces acting on the infalling material as compared to the results of Yorke & Bodenheimer (1999) without such a detailed dust model is slight.

b) Reduce the effective luminosity:
Yorke & Krügel (1977) solved the time dependent non-steady state accretion problem in spherical symmetry and were able to produce stars of masses 17 $M_\odot$ and 36 $M_\odot$ from clouds of masses 50 $M_\odot$ and 150 $M_\odot$ respectively — due to the effects of oscillatory "super-Eddington" accretion. Accretion was permitted during quiescent low luminosity phases. Also, the sheer weight of the entire dusty envelope forced material upon the star, even when the Eddington criterion was not fulfilled locally.

Nakano et al. (1995) tried to circumvent the issue of radiation pressure and the impossibility of a stationary spherically symmetric accretion flow by pointing out that, after all, we expect accretion to proceed in 2D through an accretion disk, i.e. radiation pressure would blow away the tenuous polar regions but not the massive disk. In the numerical simulations of Yorke & Bodenheimer (1999) this effect was studied quantitatively. They find that whereas the central star or protostar may emit radiation isotropically, the radiation field quickly becomes anisotropic further from the center. The radiative flux in directions parallel to the rotation axis can greatly exceed the perpendicular component of radiative flux. This so-called "flashlight effect" occurs whenever a circumstellar disk forms. According to Yorke & Sonnhalter (2001; hereafter YS) the flashlight effect is strongly compounded by the frequency dependency of radiation transfer.

Although the flashlight effect allows dusty material to come close to the central source via a circumstellar disk, eventually the material to be accreted must

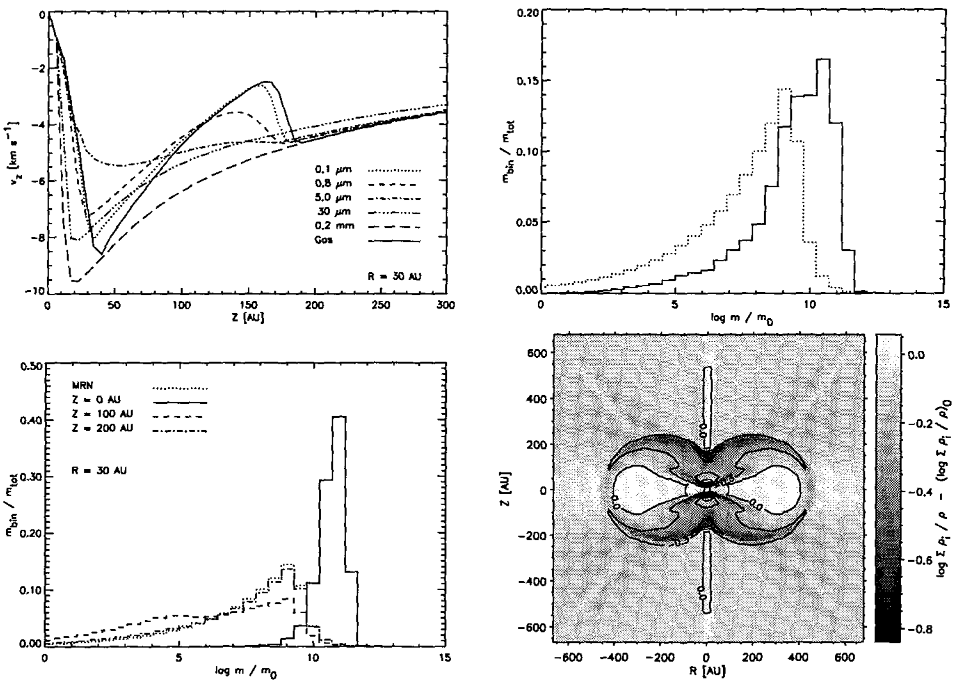

Figure 3. Evolution of compact spherical grains in a rotating, collapsing 3 $M_\odot$ protostellar clump at 11,400 yr (Suttner & Yorke 2001). **u.l.** Velocities of selected grains through the accretion shock at $r = 30$ AU. **u.r.** Evolved total dust mass spectrum (*solid line*) and initial MRN distribution (*dotted line*). **l.l.** Grain mass spectrum at selected positions along $r = 30$ AU. **l.r.** Dust to gas mass ratio (logarithmic scale). Dark regions are underabundant in dust, white regions overabundant.

encounter non-reprocessed optical and UV radiation from the central source. A necessary requirement for this material to be accreted rather than "blown out" by radiation is that the dust has been largely destroyed and the opacity is dominated by the gaseous component.

Apart from the uncertainty of whether material can fall onto the disk in the first place (radiation pressure already acts on the pre-disk envelope), forces within the disk also oppose disk accretion, as recent 2D frequency-dependent radiation hydrodynamic calculations by YS show. Even though no massive disk has yet been directly observed around a main sequence massive star, there is much indirect evidence that such disks exist. In their radio recombination maser studies and CO measurements Martin-Pintado et al. (1994) do find indirect evidence for both an ionized stellar wind and a neutral disk around MWC349. Moreover, several other high luminosity FIR sources — suspected embedded young OB stars — have powerful bipolar outflows associated with them (e.g., Eiroa et al. 1994; Shepherd et al. 2000). Such massive outflows are probably powered by disk accretion, and, similar to their low mass counterparts, the flow energetics appear to scale with the luminosity of the source (see Cabrit & Bertout 1992; Shepherd & Churchwell 1996; Richer et al. 2000).

If the primary source of the massive star's material is from the surrounding molecular clump via accretion, then a circumstellar disk should be the natural consequence of the star formation process even in the high mass case. However, it should be difficult to observe disks around massive stars. The high FUV and EUV fluxes associated with high mass stars will begin to photoevaporate the disks on timescales of $\sim 10^5$ yr (Hollenbach et al. 2000), which will be observable as deeply embedded UCHIIs with comparable lifetimes (Richling & Yorke 1997).

c) Increase Gravity: For completeness I mention the fact that the gravitational acceleration is enhanced with respect to radiative acceleration when massive stars form within a dense cluster of not so brightly radiating objects. For this to have a dominant effect we require that

$$\rho_{\rm objects} \gg \rho_{\rm gas} \tag{5}$$

In such a scenario one can certainly envision that in a density-peaked cluster of low mass stars embedded within a molecular cloud, the effective gravity near the cluster's center is enhanced relative to an isolated molecular cloud without the cluster and relative to off-center regions of the molecular cloud. If the existence of such an embedded low mass cluster of stars is necessary to form massive stars, isolated massive stars may not exist at all or only in very exceptional cases.

4. What happens to the central (Proto-)Star during Accretion?

Because the luminosity evolution is so critical during accretion, I describe in the following a slightly more sophisticated treatment of the time dependent history of the radius R_*, luminosity L_*, and effective temperature $T_{\rm eff}$ of the central object than generally considered in numerical collapse calculations. This procedure was first used by YS.

For homogeneously mixed gaseous spheres knowledge of the star's mass M_* and radius R_* are sufficient to construct a unique stellar structure model

(Vogt-Russell conjecture; see discussion by Kippenhahn & Weigert 1990):

$$\rho = \rho(M_r) \qquad T = T(M_r) \qquad X_i = X_i(M_r) \quad , \tag{6}$$

where X_i is the relative abundance of element "i". From these known quantities, it is possible to determine the total (internal + gravitational potential) energy of the star:

$$E_{\text{tot}} = -\frac{\eta G M_*^2}{R_*} , \tag{7}$$

where $\eta \sim \mathcal{O}(1)$ depends on the details of the stellar structure. For a polytrope of $n = 3/2$ (e.g. a fully convective homogeneous star) $\eta = 3/7$. In general,

$$\eta = \eta(M_*, R_*) \quad \text{and} \quad L_* = L(M_*, R_*) \quad T_{\text{eff}} = T_{\text{eff}}(M_*, R_*) \tag{8}$$

Because we know the internal structure of the star, we can also determine the deuterium burning rate in the pre-main sequence phase

$$L_D = \int_0^{M_*} \epsilon_D \, dM_r \approx L_0(M_*) \left(\frac{\chi_D}{\chi_{D,0}}\right) \left(\frac{R_0(M_*)}{R_*}\right)^p , \tag{9}$$

where L_0 and R_0 are the deuterium burning rate and equilibrium radius for a star of mass M_* at its "birthline". Because the central deuterium burning rate depends so strongly on both the central density and temperature of the star (both of which in turn depend on the star's radius R_*), I have chosen the exponent p to be an appropriately large number, e.g. $p = 15$ to insure that L_D increases dramatically when $R_* < R_0(M_*)$ and decreases sharply when $R_* > R_0(M_*)$.

Assuming instantaneous mixing during accretion, the deuterium mass fraction χ_D can be calculated from the following equation:

$$\frac{d\chi_D M_*}{dt} = \chi_{D,0}\dot{M}_* - \phi_D L_D , \tag{10}$$

where $\phi_D L_D$ is the rate of deuterium consumption due to deuterium burning ($\phi_D = 1.76 \times 10^{-19}\,\text{s}^2\,cm^{-2}$ is a constant).

Energy balance dictates for an accreting star (when mass is added ever so gently) that ($\beta < 1$ but $\beta \approx 1$)

$$L_* = L_D - E_{\text{tot}} \left[\frac{\dot{\eta}}{\eta} + \frac{2\dot{M}_{\text{acc}}}{M_*} - \frac{\dot{R}}{R_*}\right] - \frac{\beta G M_* \dot{M}_{\text{acc}}}{R_*} , \tag{11}$$

Note that because $\eta = \eta(M_*, R_*)$ equation 11 is an implicit equation for $\dot{R}/R_*$ when $\dot{M}_{\text{acc}}$ is known.

From knowledge of $\dot{M}_{\text{acc}}$, $M_* = \int \dot{M}_{\text{acc}} dt$, $\eta(M_*, R_*)$, $L_*(M_*, R_*)$, $L_0(M_*)$, and $R_0(M_*)$ I approximate the pre-main sequence evolution of an accreting protostar by integrating equations 10 and 11 simultaneously. The last four functions can be extracted from published tracks of non-accreting pre-main sequence stars. $\dot{M}_{\text{acc}}$ must either be specified arbitrarily or the result of a numerical collapse calculation.

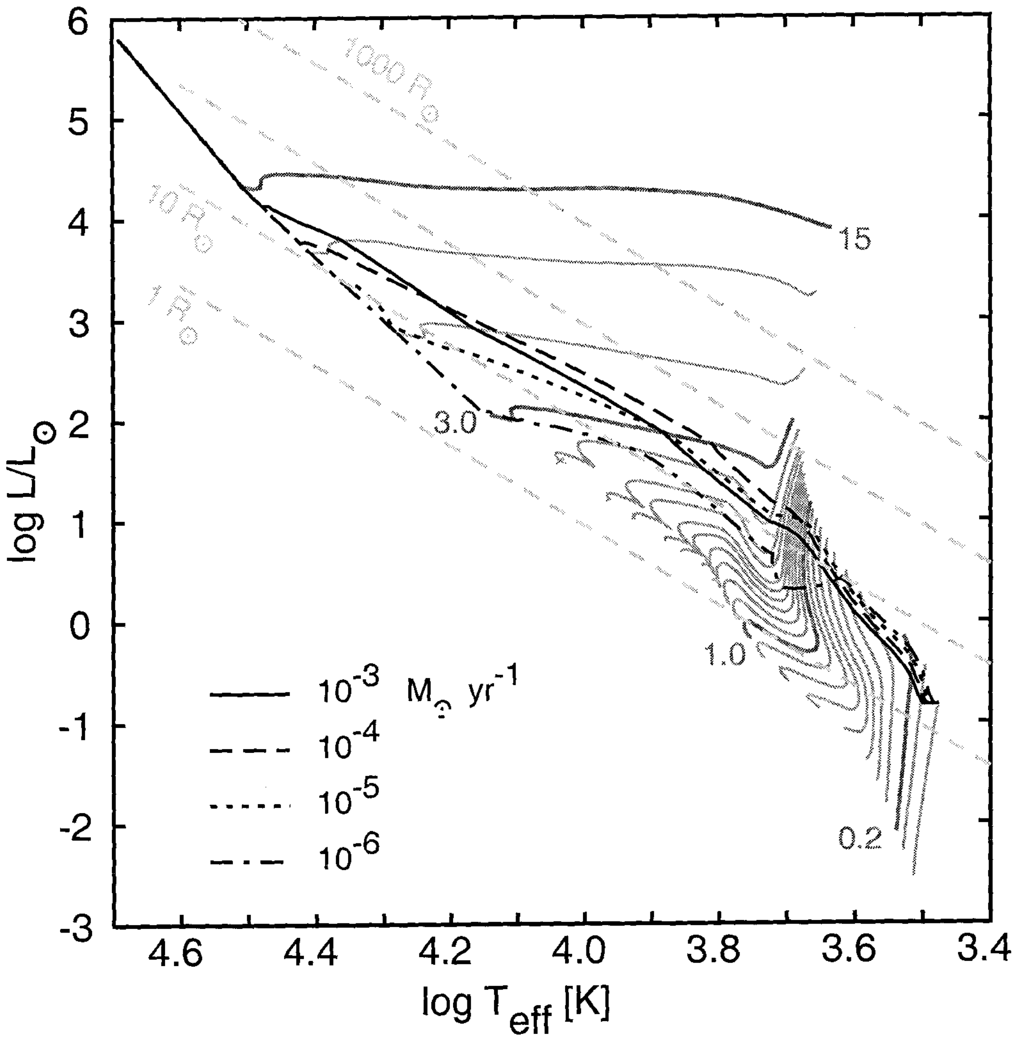

Figure 4. Pre-main sequence tracks of accreting (proto-)stars in the Hertzsprung-Russell diagram for the given constant accretion rates. All tracks except one begin at the "birthline" (where equilibrium deuterium burning occurs with ISM deuterium abundance) of a 0.1 M$_\odot$ pre-main sequence star. The case with $\dot{M}_{\rm acc} = 10^{-13}$ M$_\odot$ yr^{-1} and a starting stellar mass $M_* = 1$ M$_\odot$ at its "birthline" is indistinguishable from the corresponding 1 M$_\odot$ track of D'Antona & Mazzitelli (1994).

Examples of using this scheme to describe the evolution of accreting pre-main sequence objects are shown in Fig. 4. For 0.1 $M_\odot \le M_* \le 2.5$ $M_\odot$ the pre-main sequence evolutionary tracks by D'Antona & Mazzitelli (1994) for "CM convection" ($\alpha_{ML} = 2$) and Alexander + RI opacities ($Y = 0.28$, $Z = 0.019$) are used. For 3 $M_\odot \le M_* \le 15$ $M_\odot$ tracks published by Iben (1965) are employed.

These tracks compare very well with published, more detailed calculations by Behrend & Maeder (2001) and by Meynet & Maeder (2000; see also discussion by Maeder, this volume). Not only do the tracks lie slightly below the equilibrium deuterium burning "birthline" in all cases, but the qualitative effect of rapid accretion — namely to shift the tracks to even smaller radii below the "birthline" — occurs both in our simplified model and the above cited calculations. The reason for this is the negative sign of $2-\beta/\eta$ for fully convective stars (this is the coefficient of $\dot{M}_{acc}/M_*$ in equation 11). The tracks of our simplified model converge to the main sequence in a manner similar to those of the detailed calculations.

There are some differences, however. Behrend & Maeder and Meynet & Maeder *begin* their tracks assuming a fully convective 0.7 $M_\odot$ star taken to be 7×10^5 yr old, whereas it is shown here that the equilibrium deuterium-burning position at cosmic deuterium abundance is never reached via accretion for masses $M \lesssim 1$ $M_\odot$. If you add mass too quickly, the star's radius is reduced as discussed above. If you add it too slowly (see 10^{-5} $M_\odot$ yr^{-1} track in Fig. 4, a significant amount of the deuterium is consumed even before 0.7 $M_\odot$ has been accreted. Other differences are accountable by the different assumed time dependent accretion rates.

I remind the reader that these tracks in the HR diagram do not reflect the actual observable bolometric luminosities of accreting protostars. Much of the accretion luminosity will be indistinguishable from the intrinsic luminosity of the star.

5. The Evolution of massive collapsing rotating molecular Clumps

YS consider the collapse of isolated, rotating, non-magnetic, massive molecular clumps of masses 30 $M_\odot$ 60 $M_\odot$, and 120 $M_\odot$ using an improved frequency-dependent radiation hydrodynamics code (see Fig. 5 and Table 2 for selected results). The "flashlight effect" (Yorke & Bodenheimer 1999) — whereby radiation is both reflected and reemitted non-isotropically, particularly strongly in the polar direction — allows material to enter into the central regions through the disk. Because these simulations cannot spatially resolve the innermost regions of the molecular clump, however, they cannot distinguish between the formation of a dense central cluster or a single massive object. They also cannot exclude significant mass loss from the central object(s) which may interact with the inflow into the central grid cell. Thus, with the basic assumption that all material in the innermost grid cell accretes onto a single object, they are only able to provide an upper limit to the mass of stars which could possibly be formed.

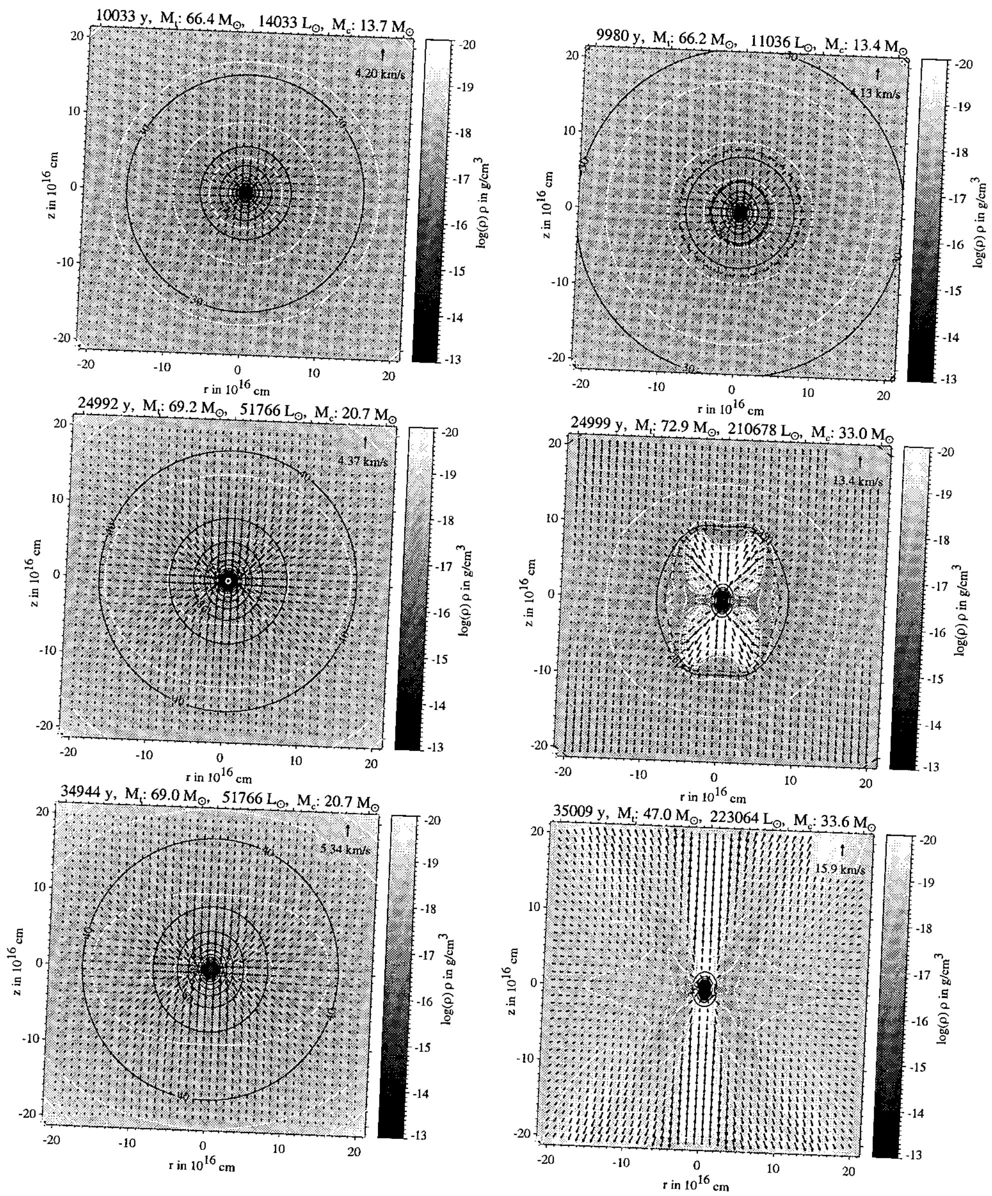

Figure 5. Distribution of density (*grey-scale* and *white contour lines*), velocity (*arrows*), temperature of amorphous carbon grains (*solid black contour lines*), and temperature of silicate grains (*dotted contour lines*) for the 60 $M_\odot$ cases calculated by YS assuming "grey" opacities (left three frames) for the given evolutionary times and assuming frequency-dependent opacities (right three frames).

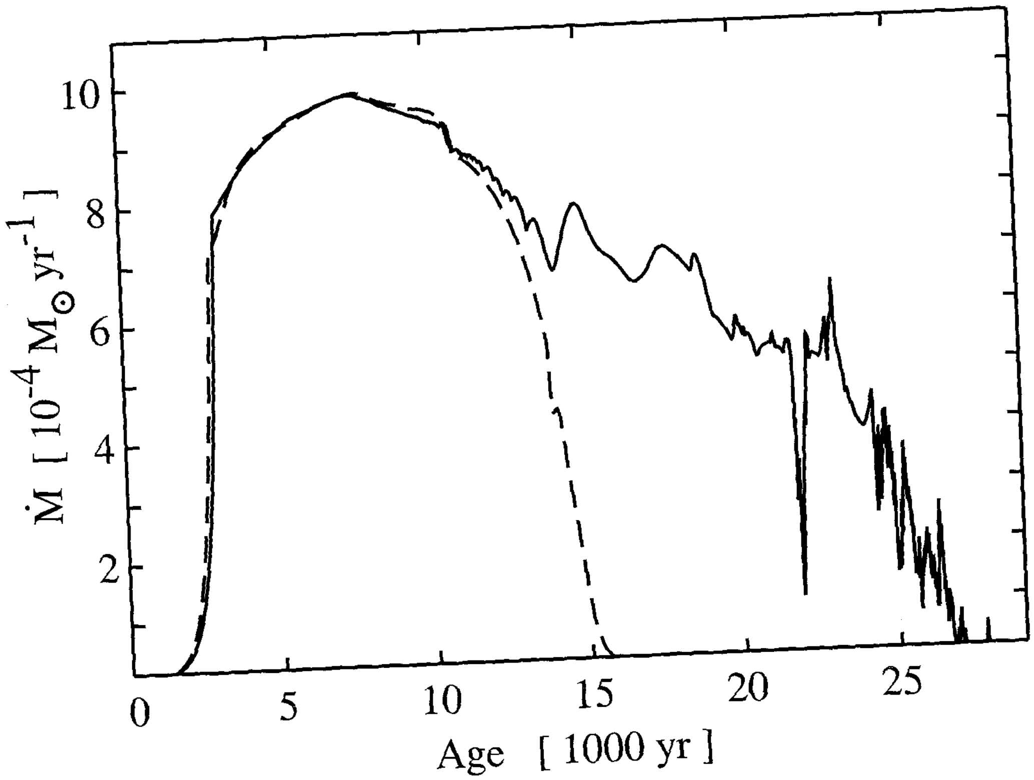

Figure 6. Mass accretion rate of central object for cases shown in Fig. 5. The evolution of $\dot{M}_{\rm acc}$ assuming frequency-dependent opacities is depicted with a solid line, whereas the comparison "grey" calculation is shown with a dashed line).

6. Discussion and Conclusions

The improved frequency dependent radiation hydrodynamics code by YS is able to track the infall of material within a molecular clump against radiative forces. The "flashlight effect" first discussed by Yorke & Bodenheimer (1999), i.e. the non-isotropic distribution of radiative flux that occurs when a circumstellar disk forms, is strongly compounded by the frequency dependent radiation transfer. The shortest wavelength radiation (which is also the most effective for radiative acceleration) is most strongly concentrated towards the polar directions, whereas the longer wavelength radiation (less effective radiative acceleration) is less directed.

Massive stars can in principle be formed via accretion through a disk, in a manner analogous to the formation of lower mass stars. This process is inefficient, only a fraction of the available material in a molecular clump can accrete onto the newly formed star. A powerful radiation-driven outflow in the polar directions and a "puffed-up" (thick) disk result from the high luminosity of the central source.

A simplified procedure is presented which traces the evolution of accreting (proto-)stars by exploiting existing tracks for non-accreting stars. Using this procedure I have shown that the concept of "birthline", the equilibrium position of fully convective, deuterium-burning stars in the HR diagram with cosmic deuterium abundance, is — strictly speaking — unattainable for stars more massive than 1 $M_\odot$. Beginning with a protostar of a fraction of a solar mass and building up via accretion to 1 $M_\odot$ and higher masses, it either accretes too rapidly (shifting the HR position to smaller radii) or it accretes too slowly (significant amounts of previously accreted deuterium are consumed). For masses $M \lesssim 10$ $M_\odot$, however, the contribution of the accretion luminosity may make the star *appear* to lie on or above the birthline. The "pre-main sequence" phase for massive ($M \lesssim 10$ $M_\odot$) is non-existent; $\dot{M}_{acc} \neq 0$ evolutionary tracks are imperative.

In this report I have not addressed the issues of the longevity of the circumstellar disk or the possible formation of a dense stellar cluster rather than a single star. However, even without the assumption of ionizing radiation, YS find that these disks are not long-lived phenomena. In the most massive cases the effects of radiative acceleration eventually disperse the remnant disks. Future studies will have to address the issues of ionization and the interactions of the

Table 2. Initial conditions and final core masses for two simulations of rotating $\rho \propto r^{-2}$ molecular clumps: "grey" assumes grey radiation transfer; "ν-dep" assumes frequency dependent radiation transfer

Mass [1] $[M_\odot]$	R_{max} [pc]	Ω_0 $[s^{-1}]$	ρ_0 $[g\ cm^{-3}]$	M_{final}^{grey} $[M_\odot]$	$M_{final}^{\nu-dep}$ $[M_\odot]$
60	0.1	5×10^{-13}	10^{-20}	20.7	33.6

[1] Material outside of R_{max} at density ρ_0 was allowed to flow into computational domain

disk with powerful stellar winds. The effects of nearby companions in a dense stellar cluster will also have to be considered in future work.

Acknowledgments. This research was conducted at the Jet Propulsion Laboratory, California Institute of Technology and has been supported by the National Aeronautics and Space Administration (NASA) under the auspices of the "Origins" Program and grant NRA-99-01-ATP-065.

References

Behrend, R., Maeder, A. 2001, A&A, 373, 190

Bonnell, I.A., Bate, M.R., Zinnecker, H. 1998 MNRAS, 298, 93

Cabrit, S., Bertout, C. 1992, A&A, 261, 274

D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467

Eiroa, C., Casali, M. M., Miranda, L. F., Ortiz, E. 1994, A&A, 290, 599

Hollenbach, D., Yorke, H.W., Johnstone, D. 2000, in *Protostars and Planets IV*, eds. Mannings, Boss, Russell, (Tucson: Univ. Ariz. Press), p. 401

Iben, I., Jr. 1965, ApJ, 141, 993

Kahn F.D. 1974, A&A, 37, 149

Kippenhahn, R., Weigert, A. 1980, Stellar Structure and Evolution, Heidelberg: Springer Verlag

Mathis, J.S., Rumpl, W., Nordsieck, K.H. 1977, ApJ, 217, 425

Martin-Pintado, J., Neri, R., Thum, C., Planesas, P., Bachiller, R. 1994, A&A, 286, 890

Meynet, G., Maeder, A. 2000, A&A, 361, 101

Nakano T., Hasegawa T., Norman C. 1995, ApJ 450, 183

Richer, J. S., Shepherd, D. S., Cabrit, S., Bachiller, R., Churchwell, E. 2000, in *Protostars & Planets IV*, eds. Mannings, Boss, Russell, (Tucson: Univ. Ariz. Press), p. 867

Richling, S., Yorke, H.W. 1997, A&A, 327, 317

Sheperd, D. S., Churchwell, E. 1996, ApJ, 472, 225

Suttner G., Yorke H.W. 2001, ApJ, 551, 461

Wolfire M.G., Cassinelli J.P. 1987, ApJ, 319, 850

Yorke, H.W., Bodenheimer, P. 1999, ApJ, 525, 330

Yorke, H.W., Krügel, E. 1977, A&A, 54, 183

Yorke, H.W., Sonnhalter, C. (YS) 2001, ApJ, in press